Spectral analysis of red scattered sunlight at sunrise

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Abstract

We analyze and fit visible spectra of a red horizon at sunrise. The shape of the spectra consist of a blue continuum followed by a red bump.

The reddest spectra are well fitted by the product of a spectrum of extinguished sunlight (Rayleigh extinction + ozone absorption) and of $1/\lambda^4$. The former is essentially the radiation field in the outer atmosphere, at the scattering volume location; the latter corresponds to Rayleigh scattering by the gas.

Moving to higher altitudes, a second component, corresponding to the spectrum of a blue sky, must be added.

The spectra we have obtained are similar to spectra of red nebulae, suggesting there may be other explanations than an emission process to the red color of some nebulae.

Key words: atmospheric effects; diffusion; scattering; radiative transfer
PACS: 42.68.J, 42.68.A,, 94.10.G, 92.60, 03.80, 94.10.L, 92.60.E, 51.20, 95.30.Jx

1 Introduction

In a preceding paper (Zagury & Goutail, 2003), we have analyzed spectra of the sun observed through layers of the atmosphere at increasing optical

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arXiv:astro-ph/0601152v1 7 Jan 2006

depths.

This study helped define what the radiation field at any point of the atmosphere, in normal conditions, should be. It was also remarked that the light received at the earth's from a direction different than that of the sun, should be the product of the radiation field in the atmosphere and $1/\lambda^4$.

In the present article, we will be interested in the nature of the glow horizon observed from earth at sunrise, or sunset.

2 Data

The data was acquired at the Fujii Bisei Observatory (Bisei Okayama, Japan, http://www1.harenet.ne.jp/~ aikow/). The telescope is a 28 cm reflector. The slit width of the spectroscope is 0.1 mm with a dispersion of 32.8 nm/mm. The spectral resolution is 1 nm. The wavelength range sampled by the spectrograph is 4400 Å to 7150 Å.

For this observational program, morning grow spectra, and near zenith blue skys, were obtained during three observing runs, in the early mornings of November 11, 2001, January 11, 2002 and June 1, 2002. November 2001 and January 2002 spectra are observations of the red horizon at sunrise, at different elevations. The three spectra of June 2002 are blue sky, high altitude spectra. The blue spectra are proportional one to the other, so that only one is used in the paper. The sky was clear for the three observing runs. Information on the observations is given in Table 1.

A dark exposure is substracted from the raw spectra. The spectra are then flat-fielded using the spectrum of a tungsten lamp. We did not require an absolute calibration for the spectra since we were interested only by their shape. The spectra presented in the paper are all normalised by a spectrum of the sun, kindly furnished by G. Thuillier (Thuillier et al., 2003). The normalised spectra are set to 1.0 in their short wavelength part.

3 Analysis

3.1 General considerations on the shape of the spectra

Run 1 and run 2 spectra are separately plotted in Figure 1. Moving from the near-UV to the near-infrared, the spectra consist in an exponential decrease
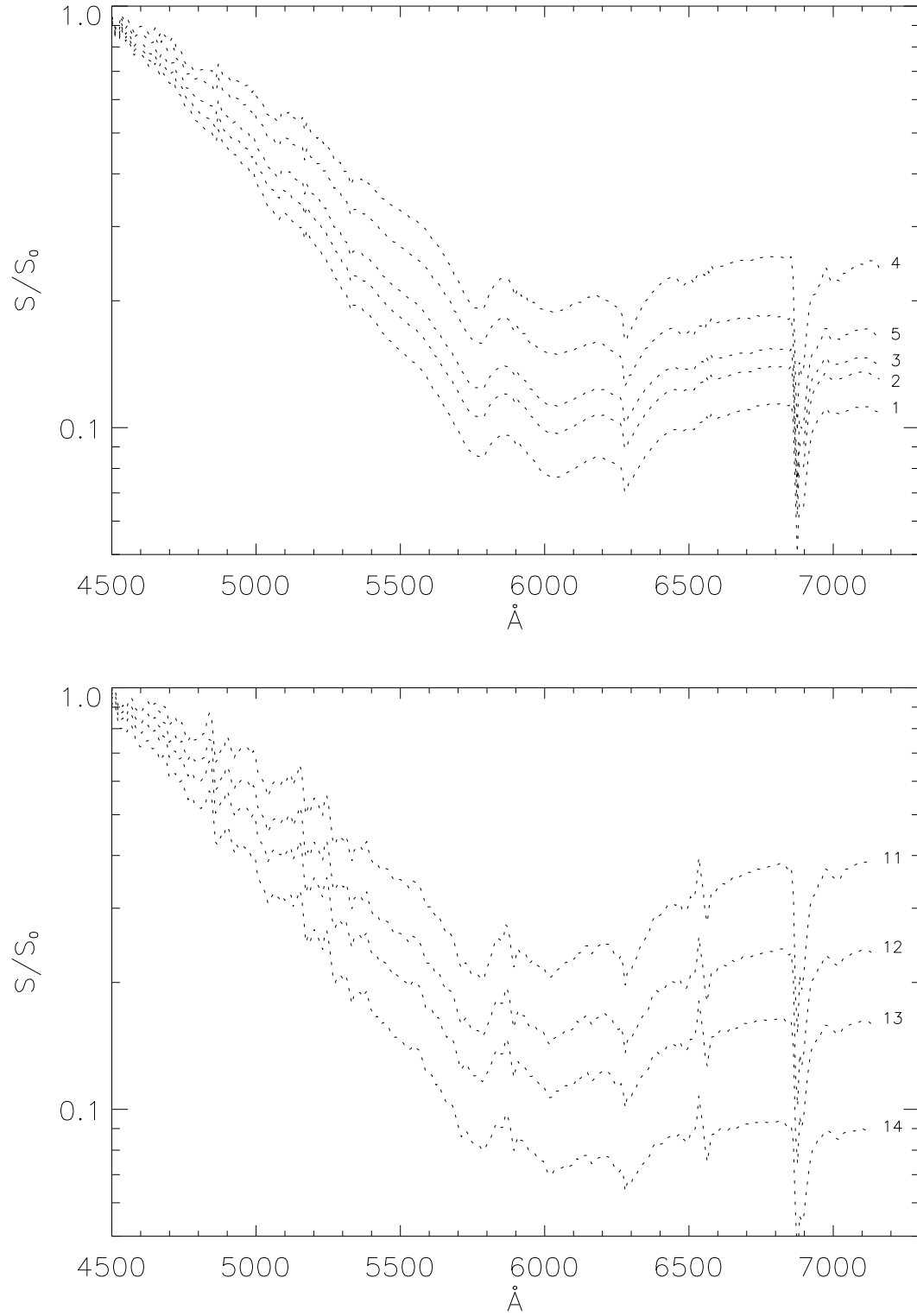
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Fig. 1. Spectra of the glow at sunrise observed from Fujii Bisei Observatory. The spectra are labeled by their number in Table 1 (first column). The spectra are normalized to 1.0 in the blue. *Top:* November 2001 data. *Bottom:* January 2002 data.

Table 1

Parameters for the spectra used in the article

n° [1]	U.T. [2] h:min:sec	exposure [3] sec	altitude (°)	azimuth (°)	angular distances from the sun (°)
November 2001					
1	21:15:39	24	45.35	270.28	52
2	21:18:25	12	30.59	269.35	39
3	21:20:44	10	20.87	269.28	31
4	21:26:15	1.0	7.15	270.30	21
5	21:28:36	1.2	10.57	270.55	23
January 2002					
11	21:56:14	5	7.7	295.9	12
12	21:57:53	8	13.3	296.0	17
13	21:59:49	10	23.1	296.5	27
14	22:02:06	12	69.5	303.0	73
June 2002					
b1	22:36:14	0.20	64.6	59.5	82.7
b2	22:37:52	0.22	64.3	60.0	82.7
b3	22:39:27	0.18	64.0	60.6	82.7

(1) This number is used in the text and in the figures for the corresponding spectra.

(2) Time of observation. Local time is: U.T.$+09^{h}$.

(3) Duration of exposure.

followed by a red bump.

For each run there is a straightforward relation between the altitude of the observation, the slope of the blue decrease, and the importance of the red bump: the closer to the horizon (lowest altitude) the observation is, the smoother the slope, and the more important is the bump. The impression of 'red', one has when looking at the horizon at sunrise or sunrise, depends on the level of the bump.

The blue spectra consist of the exponential decrease solely (left plot of Figure 2); the red bump has disappeared. These high altitude observations of a clear sky must be backscattering of slightly extinguished sunlight from the
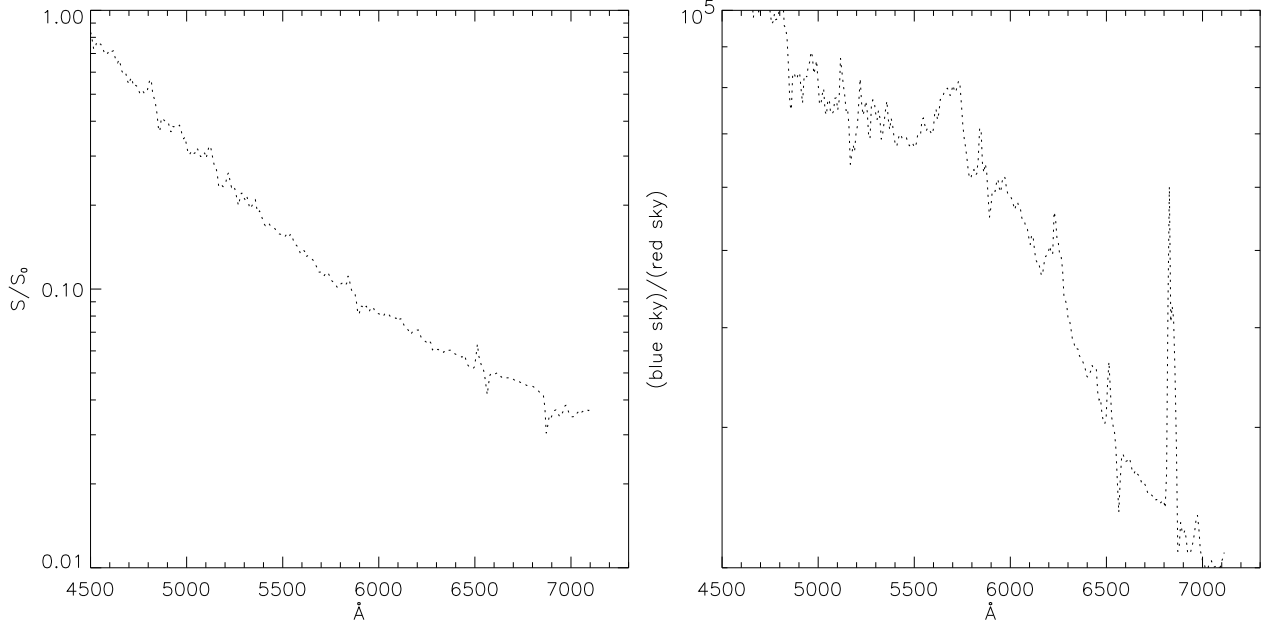
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Fig. 2. Spectrum of a blue sky observed from Fujii Bisei Observatory. *left:* Spectrum (b1) observed in June 2002. *right:* Ratio of a blue sky spectrum (spectrum (b1)) to a red sky spectrum (spectrum (4)).

atmosphere along the line of sight.

For reasons of continuity, the blue part of the red spectra at the highest altitudes probably comprise a part of slightly extinguished scattered sunlight, with a spectrum similar to the blue light spectrum.

The reddest spectra are the result of a longer optical paths of the sunlight - necessarily through the outermost part of the atmosphere- followed by scattering. Since the outer atmosphere is mainly gas, the red spectra can be expected to be a mixture of gas extinction of sunlight between the sun and the scattering volume (Rayleigh extinction e^{-a/λ^4} + ozone absorption with cross-section $\sigma_\lambda, = e^{-N_{O_3}\sigma_\lambda}$), followed by Rayleigh scattering ($\propto 1/\lambda^4$).

The presence of important absorption by ozone in the red spectra is manifest in the ratio of blue to red spectra (the bump in the $5000\,\text{Å}$ to $6500\,\text{Å}$ wavelength region, right plot of Figure 2). Empirical relations between the red spectra also confirm the importance of ozone absorption: the blue parts of the red spectra deduce one from the other by an exponential of $1/\lambda$ (Figure 3). Similar relations, with exponents of opposit sign, exist between the red parts of the spectra. These relations can be related to the extinction cross section of ozone (Zagury & Goutail, 2003), σ_λ, which is linear in $1/\lambda$ from $1.4\,\mu\text{m}^{-1}$ to $1.7\,\mu\text{m}^{-1}$ (with a positive slope) and from $1.7\,\mu\text{m}^{-1}$ to $2\,\mu\text{m}^{-1}$ (with a negative slope).

It follows that the blue decreases in the red spectra can have two origins: blue light scattered by the inner parts of the atmosphere, or absorption by ozone.

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Table 2
Fits used in Figure 4 and Figure 5

n°	Fit [1]
Red (lowest latitude) spectra (Figure 4)	
4	$\propto e^{-2.2\,10^{20}\sigma_\lambda}e^{-0.032/\lambda^4}/\lambda^4$
5	$\propto e^{-2.0\,10^{20}\sigma_\lambda}e^{-0.014/\lambda^4}/\lambda^4$
11	$\propto e^{-2.8\,10^{20}\sigma_\lambda}e^{-0.055/\lambda^4}/\lambda^4$
12	$\propto e^{-2.3\,10^{20}\sigma_\lambda}e^{-0.030/\lambda^4}/\lambda^4$
13	$\propto e^{-2.3\,10^{20}\sigma_\lambda}e^{-0.010/\lambda^4}/\lambda^4$
Red spectra with a blue sky component (Figure 5)	
1	$\propto e^{-2.7\,10^{20}\sigma_\lambda}e^{-0.001/\lambda^4}/\lambda^4$
2	$\propto e^{-2.2\,10^{20}\sigma_\lambda}e^{-0.015/\lambda^4}/\lambda^4$
3a	$\propto e^{-2.1\,10^{20}\sigma_\lambda}e^{-0.011/\lambda^4}/\lambda^4$
3b	$\propto e^{-2.2\,10^{20}\sigma_\lambda}/\lambda^4$
14a	$\propto e^{-2.3\,10^{20}\sigma_\lambda}/\lambda^4 + \alpha(b1)$ [2]
14b	$\propto e^{-2.3\,10^{20}\sigma_\lambda}/\lambda^4$

(1) σ_λ is the wavelength-dependent absorption cross-section of ozone.

(2) α a constant.

Finally, the red spectra should be the sum of a red and a blue components, weighted by the ozone absorption. For a given time, at a constant azimuth, the lowest latitude spectra should be dominated by the red light and an important ozone depression. This depression and the importance of the red bump will diminish with the increase of altitude. Still increasing the altitude, blue light should appear towards the near-UV first, and progressively replaces red light.

3.2 Fit of the spectra

The reddest spectra, spectra 3, 4, 5 of November 2001 and spectra 1 and 2 of January 2002, are well fitted by a function $\propto e^{-\alpha/\lambda^4 - \beta oz(\lambda)}/\lambda^4$ (Figure 4), expected for gas extinction and scattering of sunlight.

It is also possible to adjust a similar fit to the higher altitude red spectra, but the result is not as satisfying (see spectrum (3b) of Figure 5). The best
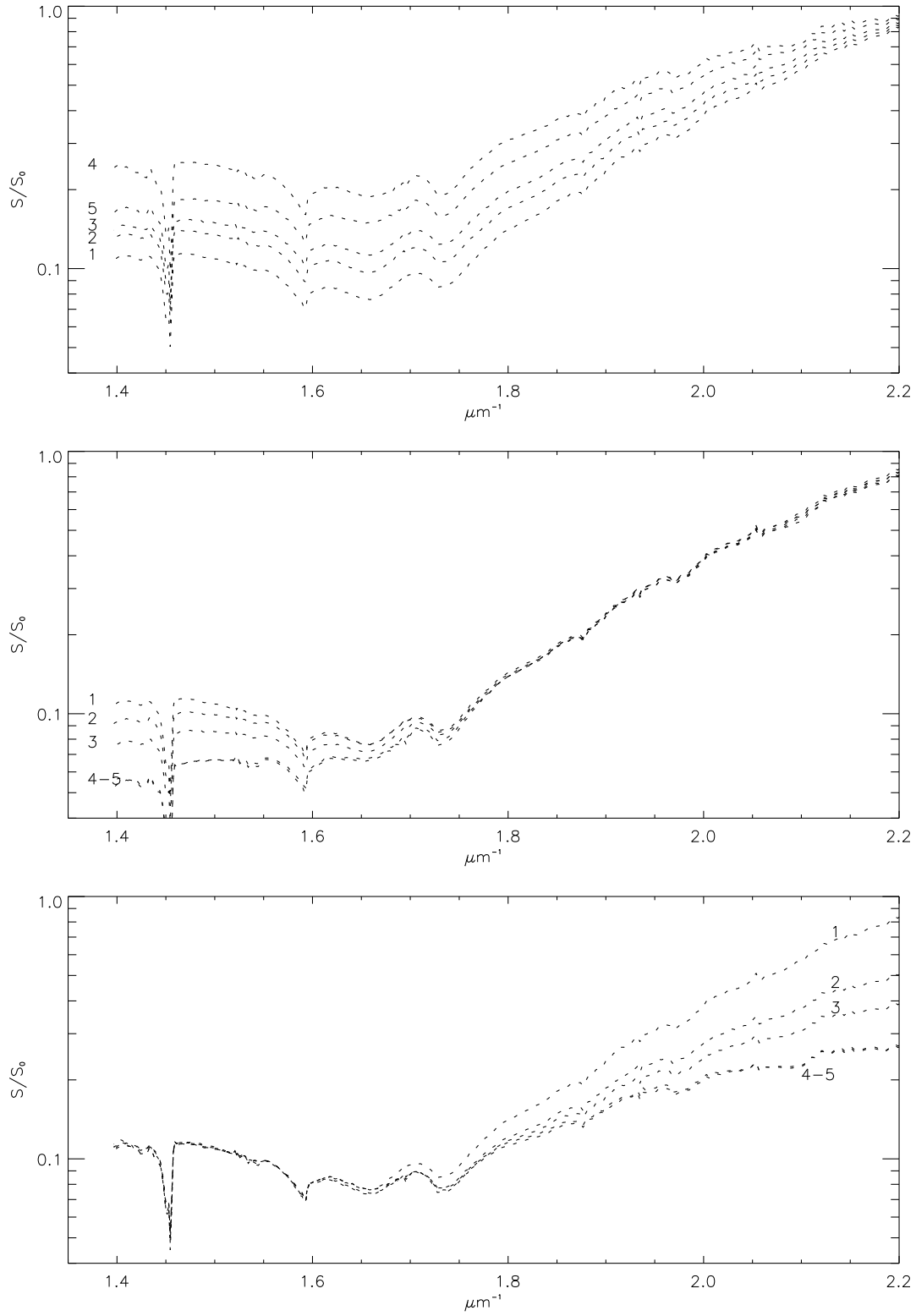
Fig. 3. *Top:* November 2001 data plotted against $1/\lambda$. *middle:* In the blue, spectra (2), (3), (4), (5) of November 2001 deduce one from spectrum (1) by an exponential of $1/\lambda$ with respective exponents 0.45, 0.7, 1.7, 1.33. *Bottom:* Same for the red part of the spectra, with exponents -0.45, -0.7, -0.6, -0.1.
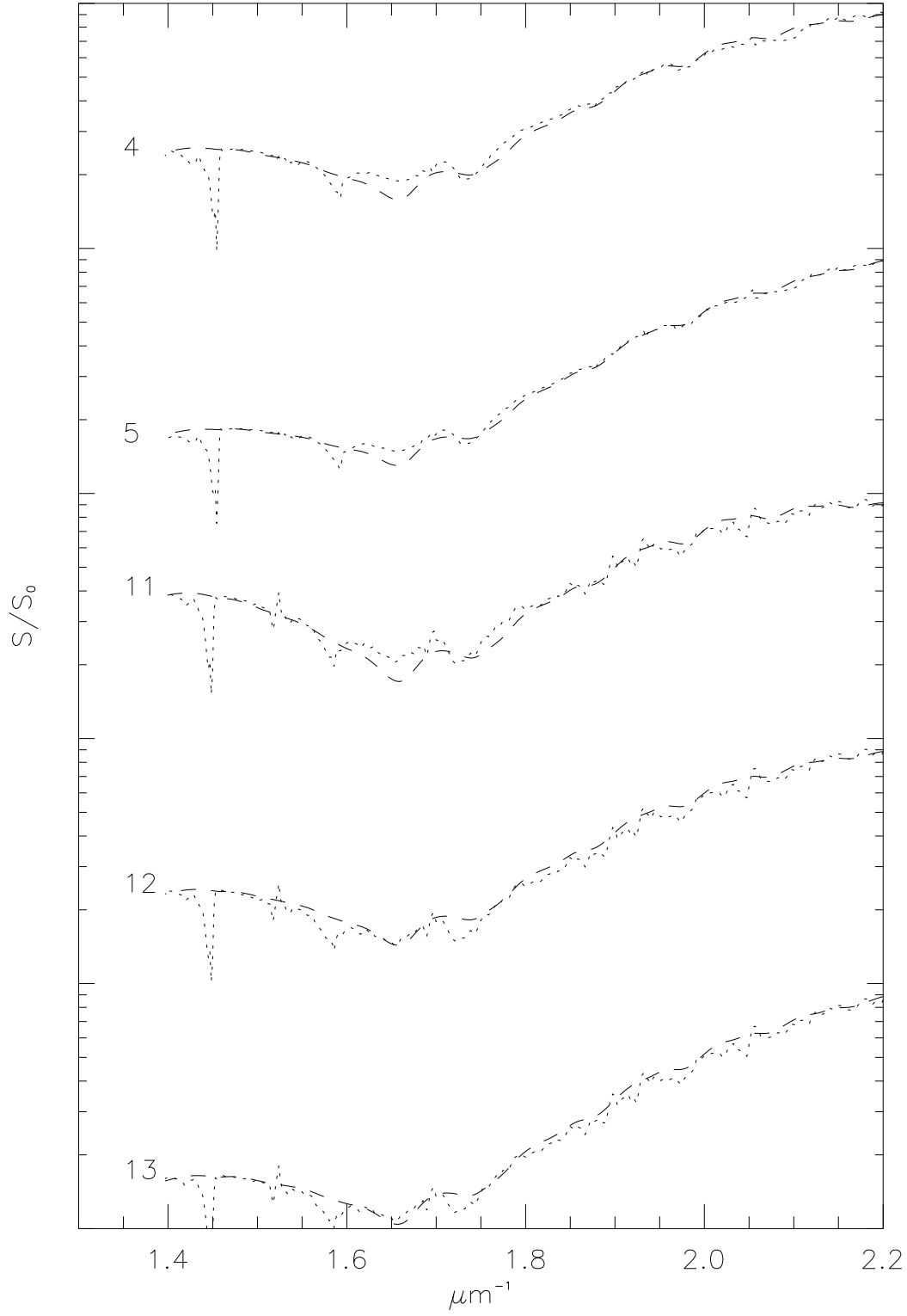
Fig. 4. Fit of the low altitude (reddest) spectra. The fit are a combination of Rayleigh extinction ($\propto e^{-a/\lambda^4 - oz(\lambda)}/\lambda^4$) and ozone absorption, in agreement with what is expected from gas extinction in the upper atmosphere.
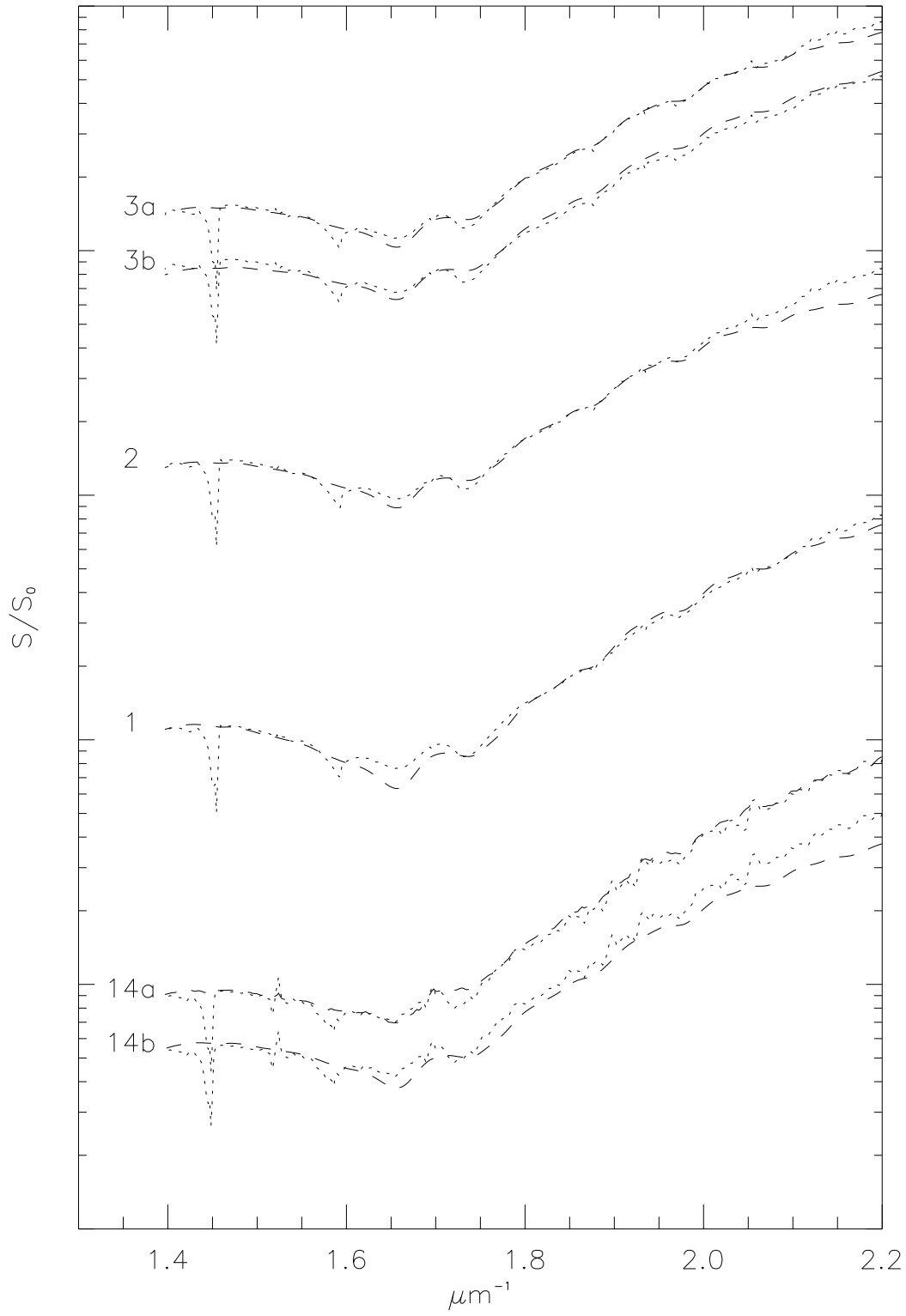
Fig. 5. For the high altitudes spectra, the fit cannot be reduced to a one component gas extinction. The fit adopted in Figure 4 is less satisfying, as shown for spectrum (3), fit (3b). This fit still applies to the red part of the spectra, but a second component is necessary to account for the blue part. For spectrum (14), the fit (14a) is a two additive components fit, one for the red part and an additional blue part proportional to blue spectrum (b1).

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fit to the red part of these spectra (Figure 5) does not account for all of the blue side. An additional component is necessary to complete the fit, which we assume is the merging blue light.

Spectrum (14a) of Figure 5 shows the fit which can be obtained by adding a fraction of blue sky (blue spectrum (1b) of June 2002) to the red fit.

We did not attempt to fit the blue spectra of June 2002, because of the difficulty of finding the proper analytical expression from these three blue spectra alone, in this limited wavelength range.

4   Conclusion

Our purpose was to understand the nature of the red light in the horizon at sunset, or sunrise, and to fit the corresponding spectra.

Contrary to what seems to be indicated, the shape of the spectra -a blue continuum followed by a red bump- spectra of a glow horizon are not simply the sum of scattered sunlight by two media (or two different kind of particles) on the same line of sight.

The reddest (lowest atltitudes) spectra of a glow horizon are due to sunlight extinguished by the gas (Rayleigh extinction + ozone absorption) in the outermost parts of the atmosphere and scattered -still by the gas (mainly nitrogen)- in the direction of the observer. Extinction of the scattered light by the gas can also happen but should be a minor effect. In any case, this will not change the analytical expression of the fit.

The radiation field at the scattering volume location is the simplest one observed by the SAOZ balloon experiment (Zagury & Goutail, 2003) and scales as $e^{-a/\lambda^4 - N_{O_3} oz(\lambda)}$. The scattered light received at the earth's surface is the product of this extinguished sunlight and of $1/\lambda^4$.

Towards the longer wavelengths, Rayleigh extinction is less important; the red spectra must vary as $1/\lambda^4$ (the e^{-a/λ^4} term becomes negligible). Thus, we can predict that the long wavelength part of the red bumps will vary as $1/\lambda^4$.

The impression of 'red' has two origins. One is due to the average slope of the spectra, more pronounced when moving to higher altitudes and bluer regions of the sky. Second, this impression is increased by the ozone deficit feature, especially towards the lowest altitudes, because of a larger optical path and ozone absorption in the outermost atmosphere. The longest the optical path of sunrays at the horizon, the redder the spectrum will appear.

At intermediate altitudes, in between the red light at low altitude and the blue near-zenith sky, we found transition spectra which are the sum of a blue component and of a red one.

There are striking similarities between the spectra presented here and the spectra of some red nebulae, the best example being spectra in Orion observed by Perrin & Sivan (1992). It is currently admitted that the red color of these nebulae must result from an emission process. The example of the red horizon suggests the possibility of other explanations for the red color of these nebulae.

References

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